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Original scientific paper

A comparative study of probability distribution models for flood discharge estimation: Case of Kravga Bridge, Turkey

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Due to climate change, floods have been more frequent in recent years. Estimating the flood discharge as a result of flood frequency analysis is very substantial to make necessary preparations for possible floods. Data covering 36 years were collected from different stream gauging stations (SGS No: D17A016 and EIEI 1731) in Eastern Mediterranean Basin. With these data, flood discharge values were computed for return periods of 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years. Normal, Log-Normal, Gumbel, Pearson Type III and Log-Pearson Type III statistical distribution methods were used. Kolmogorov-Smirnov (K-S) and Chi-square goodness-of-fit tests were performed to determine which distribution fitted the flood discharge the best. The study showed that the highest flood discharge among the probability distributions for both SGSs came from the Log-Normal distribution, and the lowest discharge was calculated with the Normal distribution. The K-S tests showed that all probability distributions conformed to the 20% significance level. For SGS D17A016, the flood values calculated with Log-Normal distribution were compatible with a 90% confidence interval according to the Chi-square test. Flood values obtained with the other distributions were found within the 10% significance level. In the Chi-square test for SGS EIEI-1731, all probability distributions fell within a 10% significance.

Keywords: flood frequency analysis, probability distribution functions, goodness-of-fit tests, return periods, Kravga Bridge, Turkey

1. Introduction

Floods are natural disasters that threaten human and living life significantly. Over the years, many people around the world have been affected by flood disasters and they have caused severe damage to property (Doocy et al., 2013; Bhat et al., 2019). Increasing population and a considerable increase in land use have intensified the applications on the floodplains, so the flood damages have become even greater. Faulty flood control practices further increased the destructive effects of floods. It was reported that there are more and more floods each year due to climate variability globally (Kundzewicz et al., 2019). Being able to reveal the causes of floods and the benefits of taking safety measures will raise awareness of flood management (Šugareková and Zeleňáková, 2021). One of the types of research that can be conducted to reduce flood damage is to calculate the maximum flow rates of the floods for varied return periods using the recorded flow data (Debele et al., 2017; Farooq et al., 2018; Bhat et al., 2019; Młyński et al., 2020; Samantaray and Sahoo, 2020). In this context, it is of the utmost importance to deal with structural measures first and then to prepare contingency action plans for floods with non-structural solutions.

Collecting all the hydrological data quantitatively is often a difficult procedure. On the other hand, making predictions through statistical methods that make use of measured data has great advantages (Yılmaz and Önöz, 2019; Langat et al., 2019; Hu et al., 2020; Hamzah et al., 2021). For this purpose, flood return periods can be calculated by implementing probability distribution functions in flood frequency analysis (FFA) studies. Discharges can be obtained for different return periods from the recorded flow data (Bhat et al., 2019; Hasan, 2020; De Souza et al., 2021). The analysis of data acquired from observations over many years will make a major contribution because of the accuracy of the results (Machado et al., 2015; Hu et al., 2020). FFA can be easily done with the help of many statistical distribution functions, including Normal, Log-Normal, Gumbel, Pearson Type III, Log-Pearson Type III, Weibull, Generalized Extreme Value, and Generalized Logistic functions. There are many studies in the literature in which these distributions are used (Zhang et al., 2017; Farooq et al., 2018; Bhat et al., 2019; Langat et al., 2019; Samantaray and Sahoo, 2021; Sahoo and Ghose, 2021; Umar et al., 2021; Mangukiya et al., 2022).

FFA is directly related to the life and cost of water structures in terms of hydrology (Leščešen and Dolinaj 2019; Hamzah et al., 2021). Therefore, it is necessary to make accurate estimations of the flow rate for divided return periods. In the literature, there are studies in which flood discharge was calculated for several return periods (Kamal et al., 2017; Garmdareh et al., 2018; Bhat et al., 2019; Kousar et al., 2020; Mangukiya et al., 2022). Design flow rates are derived from the annual maximum discharges observed over many years. Since estimations are made through appropriate probability distribution functions using those observations, gaps and errors in recorded data can greatly affect the results (Saghafian et al., 2014; Bhat et al., 2019). It has been stated that it is essential to have at least 30 years of recorded data to make reliable predictions (Bhat et al., 2019; Hu et al., 2020). Consequently, 36 years of flow data without a gap were used in this study.

The Eastern Mediterranean Basin, renowned as one of the most important flood basins in Turkey, has suffered many floods over the years. There are numerous records of floods that have occurred since 1958. Most settlements in the basin have been affected negatively by this type of disaster (Eastern Mediterranean Basin Flood Action Plan, 2019). Recently, flood risks have soared notably due to the effects of increased population, land uses and construction. Contingency action plans are prepared to prevent possible floods. Since discharge estimates are very important in the design of action plans, flood data tested by goodness-of-fit tests are needed for different and more frequent return periods. Therefore, in this study, the flood magnitudes at two stream gauging stations close to each other in the Eastern Mediterranean Basin were calculated by Normal, Log-Normal, Gumbel, Pearson Type III and Log-Pearson Type III probability distribution functions for various return periods such as 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years. The appropriate distribution of the obtained flood discharge was determined with Kolmogorov-Smirnov (K-S) and Chi-square goodness-of-fit tests, which are frequently used in the literature. The optimal probability distribution function was determined by involving compliance tests as well. As a result, it has been investigated to what extent the frequency and calculated discharge in flood periods can be correctly correlated for stations close to each other. These analyses can serve as effective input in planning prospective water structures. Comparing the data from gauging stations in close proximity to each other by using several probability distributions and investigating them with compliance tests is a valuable contribution to the literature.

2. Materials and methods

2.1. Case study

The Eastern Mediterranean Basin is situated in the south of Turkey between latitudes 36°00' and 37°28' North and longitudes 32°06' and 35°09' East. The basin has an area of approximately 2,180,704 hectares (ha), about 3% of Turkey's surface area. The length of the basin is around 129 km. It has a total precipitation area of 21,807 km^2. The yearly average precipitation is 745 mm, and the average discharge is stated as 11.07 km^3 per year. There are many fertile plains in the thin strip of the basin between the coast and the mountains (Eastern Mediterranean Basin Drought Management Plan, 2018). Within the scope of this study, the historical Kravga Bridge was selected as the application site for flood analysis. This bridge was built in ancient times on the Göksu River in the basin and has faced the danger of flooding for years. Triangular protrusions were built on its piers to reduce the possible flood risk (Sözlü, 2017). There are nearly 100 SGSs throughout the basin, and the flood flows were calculated for various return periods using the data from two stations close to the Kravga Bridge. The data used in the study come from the 36-year maximum flow data between 1980 and 2015 from the SGSs numbered D17A016 and EIEI-1731 (DSI, 2015) (Fig. 1).

Various statistical parameters needed to be derived from the available data to calculate the flood discharge in the return periods. The statistical parameters utilized for this study are given in Tab. 1.

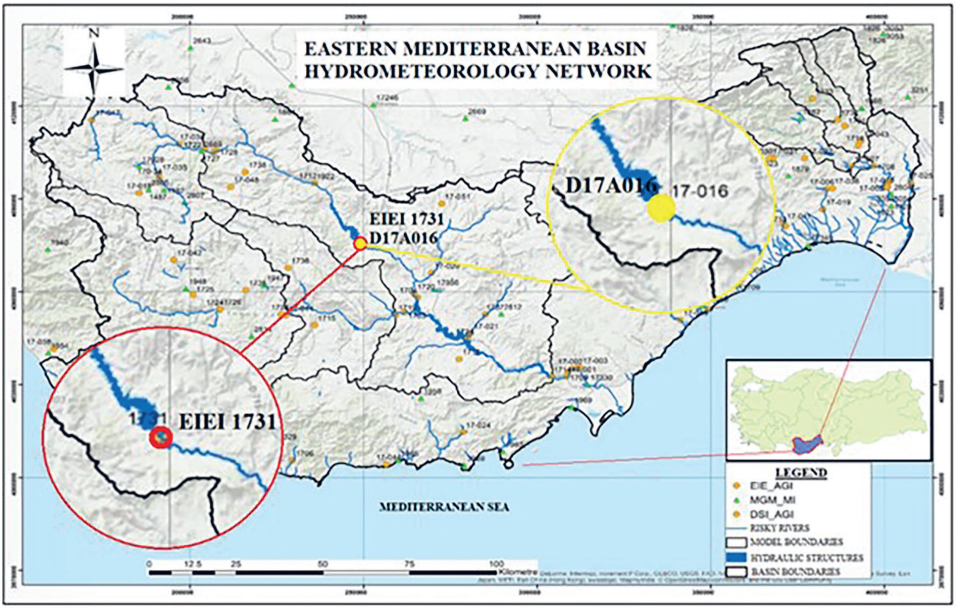

Figure 1. Stream gauging stations close to Kravga Bridge (Eastern Mediterranean Basin Flood Action Plan, 2019).

Table 1. Statistical values of Stream Gauging Stations (SGSs).

SGS No	Mean (m^3/s)	Standard deviation	Kurtosis (C_{sx})	Kurtosis (C_{sy})	Drainage area (km^2)	Duration of records (years)
EIEI-1731	212	106.09	1.171	–0.217	2994	1980–2015
D17A016	286	115.19	0.74	–0.56	2994	1980–2015

2.2. Probability distribution functions

2.2.1. Normal distribution

Normal distribution, a function generally used in statistical calculations, is used to describe continuous probability distributions that differ from each other in terms of mean and standard deviation. The Normal distribution consists of a symmetrical bell-shaped curve (Ahsanullah et al., 2014). For a continuous random variable $x \sim N(\mu, \sigma^2)$, $P(x)$ can be represented in the interval $-\infty < x < +\infty$ as seen below:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}, \tag{1}$$

and

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-(y-\mu)^2/2\sigma^2} \mathrm{d}y \,. \quad (2)$$

The parameters μ and σ in Eqs. (1) and (2) symbolize the position and scale parameters, respectively. The density function of the Normal distribution is presented in Eq. (3):

$$Z = (x - \mu) / \sigma \,. \quad (3)$$

2.2.2. Log-Normal distribution

The Log-Normal distribution can be described as the transformation of a random variable into a Logarithmic Normal distribution (Suhartanto et al., 2018). Given that the variable *Y* has a Normal distribution, the expression $x = e^y$ represents the Log-Normal distribution. Hence, the Normal distribution function was adjusted to the Log-Normal distribution and Eq. (4) is obtained:

$$P(x) = \frac{1}{\sigma_{y\sqrt{2\pi}}} e^{\left[-\frac{1}{2}\frac{(\ln x - \mu y)^2}{2\sigma_y^2}\right]\frac{1}{x}} \,, \quad (4)$$

where μ_y is the logarithm of the mean of the yearly maximum flow rate; σ_y is the logarithm of standard deviation of the annual maximum flow rates.

2.2.3. Gumbel distribution

In the Gumbel distribution, the probability distribution function is given in its general form as in Eq. (5) (Eke and Hart, 2020):

$$P(x) = \frac{1}{\beta} e^{-\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\mu}{\beta}}} \,. \quad (5)$$

In this equation, when both position and scale parameters μ and β are set to zero, the standard Gumbel distribution function is derived (Eq. (6)). p is indicated as the probability of occurrence of observed events (Turhan et al., 2021).

$$P(x) = 1 - e^{-e^{-y}} \,, \quad (6)$$

y can be calculated using Eq. (7):

$$y = a(X - X_0) \,. \quad (7)$$

According to whether the number of items in the Gumbel distribution is greater or less than 30, a and X_0 are calculated as can be seen in Eqs. (8) and (9), respectively:

$$N > 30,\ a = \frac{1.28255}{\sigma_x},\ X_o = \mu_x - 0.45\sigma_x\,, \tag{8}$$

$$N < 30,\ a = \frac{\sigma_n}{\sigma_x},\ X_o = \mu_x - \ddot{Y}\frac{\sigma_x}{\sigma_n}\,. \tag{9}$$

The parameters σ_n and presented in Eq. (9) can be taken from the Fisher Tippett I table created for the Gumbel distribution, depending on the number of elements (Walega and Michalec, 2014).

2.2.4. Pearson Type III distribution

In the Pearson Type III distribution, which can be applied with the methods of maximum likelihood and moments, the average of the flow rate values μ_x can be calculated with the expression given in Eq. (10), depending on the parameters, standard deviation σ_x and frequency factor K:

$$X = \mu_x + K\sigma_x\,. \tag{10}$$

While calculating the distribution, the frequency factor (K) can be selected from the table created for the Pearson Type III distribution with the coefficient of skewness (C_{sx}) of the data set and the determined probability of exceedance (Lei et al., 2018). By substituting the obtained parameters in Eq. (10), the flood discharge of determined probability of exceedance was calculated.

2.2.5. Log-Pearson Type III distribution

Log-Pearson Type III distribution, also acknowledged as the three-parameter Gamma distribution, is fundamentally similar to the Pearson Type III distribution (Millington et al., 2011, Bhat et al., 2019). Distribution parameters of the logarithmic data set are the mean (Z_a), standard deviation (σ_y) and coefficient of skewness (C_{sy}). The logarithm of data set should be taken before applying the distribution. Then the aforementioned parameters are determined and the frequency factor (K_z) for Log-Pearson Type III is obtained for the desired return periods. K_z is tabulated as a function of the coefficient of skewness and return period (Rangsiwanichpong et al., 2017). The flood discharges in the determined return periods were calculated with the help of Eq. (11):

$$\log(Z_T) = \overline{Z_a} + K_z\sigma_z\,. \tag{11}$$

2.3. Goodness-of-fit tests

2.3.1. Kolmogorov–Smirnov test

The Kolmogorov–Smirnov (K-S) test was chosen to determine the compliance of flood discharge obtained with the probability distributions. It is derived from the principle of obtaining the maximum value of the absolute distinction between the distribution function ($F(x_i)$) and the frequency distribution ($F^*(x_i)$) (Eq. (12)). It can be said that the K-S test evaluates the greatest difference between empirical and theoretical total distribution functions (Kumar, 2019):

$$\Delta = \max_i = \left| F(x_i) - F^*(x_i) \right| , \tag{12}$$

$$F^*(x_i) = i / N , \tag{13}$$

where N is the number of elements, the hypothesis is accepted if the Δa value chosen depending on the determined significance level of a and the number of elements is larger than calculated Δ one.

2.3.2. Chi-square test (χ^2)

A sample with N elements depending on a random variable is divided into k classes and the number of elements (N_i) in each class is appointed. Denoting the probability of the flow values to be in the same class range as p_i, the Chi-square value was calculated as given in Eq. (14):

$$\chi^2 = \sum_{i=1}^{k} \frac{(N_i - N\, p_i)^2}{N\, p_i} . \tag{14}$$

The hypothesis can only be accepted if the χ^2 value is less than the value selected from this test table, depending on the number of elements and probability of exceedance (Farooq et al., 2018).

3. Results

The historical Kravga Bridge, built on the Göksu River in the Eastern Mediterranean Basin, one of Turkey's twenty-five basins, was used for the FFA study. The flow data accumulated over 36 years by the SGSs D17A016 and EIEI-1731 in the basin were used. With these data, flow rate values were computed for return periods of 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years. Normal, Log-Normal, Gumbel, Pearson Type III and Log-Pearson Type III methods of probability distribution were preferred, and K-S and Chi-square goodness-of-fit tests were performed to specify which distribution the collected flood discharge data were appropriate for. The variations in the calculated flow rates over the years are shown in Figs. (2a) and (2b).

The highest discharges for SGSs D17A016 and EIEI-1731 were observed in 2002 and 2004, respectively. In addition, when trend analysis was conducted according to the annual maximum discharge values of the basin, negative trend formation was determined for both stations (Kahya and Kalayci, 2004, Saplıoğlu et al., 2014). The flood discharge figures obtained using the probability distribu-

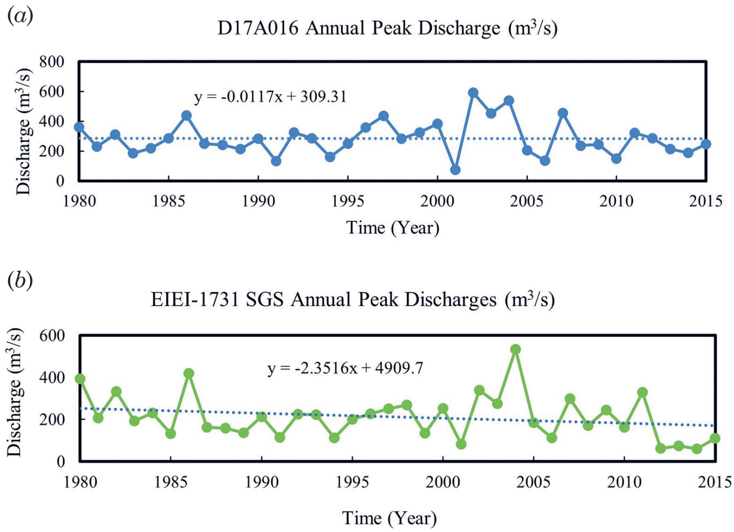

Figure 2. Graphs of discharges between 1980 and 2015.

tion functions for determined return periods using the measured annual maximal discharge values are shown in Tab. 2.

Figs. (3a) and (3b) show the discharge estimates for different return periods at SGSs D17A016 and EIEI-1731, respectively. It was seen that the discharge values of these stations grew closer to each other as the time increased in all the return periods.

Especially in the Log-Pearson Type III distribution, there was an approximation of 99% at the 1000-year return interval. Normal distribution provided the

Table 2. Estimated flood discharge values (m^3/s) using different probability distribution functions.

	No	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}	Q_{1000}
Normal	EIEI-1731	212	302	348	398	430	459	485	518	539
	D17A016	286	383	434	488	523	554	583	618	641
Log-Normal	EIEI-1731	187	292	367	469	549	632	721	848	937
	D17A016	263	377	455	555	630	707	787	898	973
Gumbel	EIEI-1731	195	289	351	429	487	545	603	679	736
	D17A016	267	369	436	521	585	647	710	792	854
Pearson Type III	EIEI-1731	192	290	354	433	490	544	598	667	719
	D17A016	272	376	440	514	565	614	661	699	765
Log Pearson Type III	EIEI-1731	191	292	362	429	517	583	650	739	908
	D17A016	274	379	440	508	553	594	631	783	913

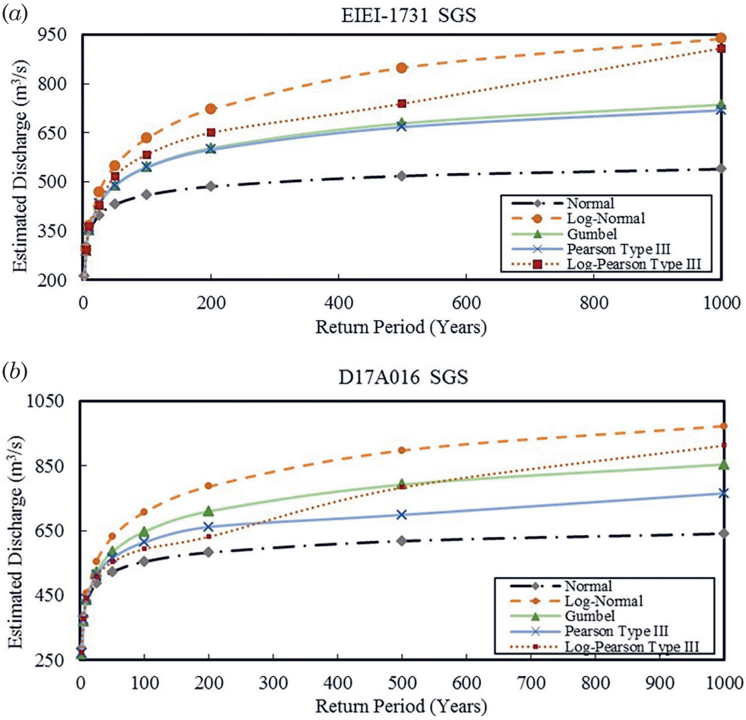

Figure 3. Discharge estimates with respect to probability distribution functions for different return periods: (*a*) SGS EIEI-1731, (*b*) SGS D17A016.

best fit for the 2-year return period, while there was high convergence for return periods of 5, 10 and 25 years. Normal distribution had minimum value for the return period of 100 years. For the 200-, 500- and 1000-year return periods, Log-Normal probability distribution also yielded high results, while the Log-Pearson Type III function showed the highest prediction 99 values. Actually, a higher discharge than expected in the 200-year return period is striking. An examination of similar studies in the literature showed that the correlation of probability distribution function results in this study is at a satisfactory level (Hanwat et al., 2020). Kumar (2019) found that Log-Pearson Type III results for a station were higher than Gumbel predictions for return periods of more than 25 years. It can be said that similar results are obtained within the scope of this study. The Log-Pearson Type III yielded the most appropriate results for return periods of 50 years or more (Pawar and Hire, 2018; Samantaray and Sahoo, 2020). The maximum flood discharge for both stations was calculated using the Log-Normal distribution, and the minimum discharge values were calculated using the Normal distribution (Fig. 4). Similar results were found in the studies by Sandalcı (2018) and Yılmaz et al. (2021).

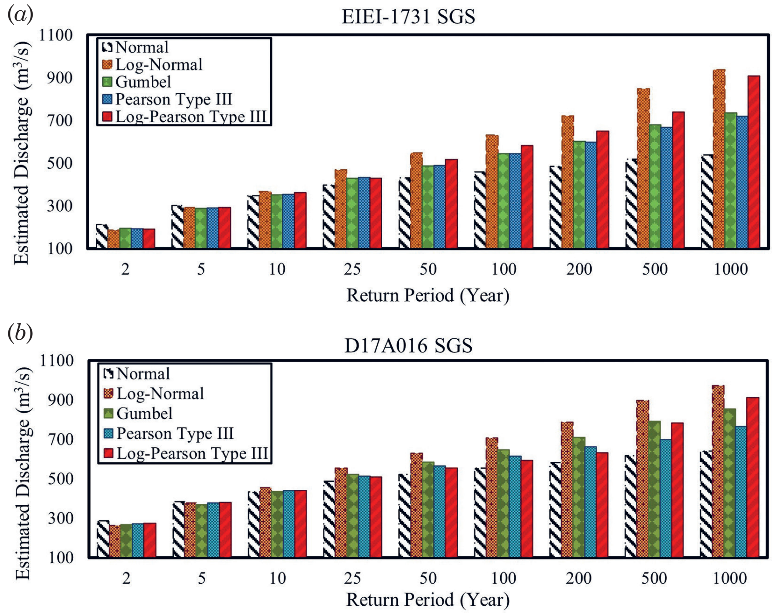

Figure 4. Comparison of flood frequency analysis results for stream gauging stations: (a) SGS EIEI-1731, (*b*) SGS D17A016.

K-S and Chi-square tests were exploited to determine the compliance level of distributions used in the discharge estimation for multiple return periods. The order of compliance of the distributions used is given in Tab 3. As a result of the K-S tests, all probability distributions were compliant at a 20% significance level, and it was determined that the Pearson Type III was the most suitable for both SGSs, as regards the level of significance. In the Chi-square tests, the lowest value for SGS EIEI-1731 was obtained with the Log-Pearson Type III distribution, while the Normal distribution gave the lowest value for D17A016 station.

Table 3. Goodness-of-fit test rankings.

	SGS	Kolmogorov-Smirnov		Chi-squared		SGS	Kolmogorov-Smirnov		Chi-squared	
		Statistic	Rank	Statistic	Rank		Statistic	Rank	Statistic	Rank
Normal	EIEI-1731	0.1144	5	0.3033	1	D17A016	0.1151	4	2.2585	5
Log-Normal	EIEI-1731	0.1056	4	1.6876	4	D17A016	0.0975	3	1.2375	1
Gumbel	EIEI-1731	0.0947	2	1.3275	3	D17A016	0.0944	2	1.4122	3
Pearson Type III	EIEI-1731	0.0896	1	0.6386	2	D17A016	0.0853	1	1.7928	4
Log Pearson Type III	EIEI-1731	0.0982	3	3.1329	5	D17A016	0.1447	5	1.3932	2

4. Discussion

In this study, Pearson Type III was determined to be optimum distribution function in terms of the K-S tests. In some applications in the literature, there was fewer error with Log-Pearson Type III distribution (Farooq et al., 2018; Kumar, 2019; Samantaray and Sahoo, 2020; Sahoo and Ghose, 2021; Umar et al., 2021). There were similar results when Chi-square tests were applied (Kamal et al., 2017; Farooq et al., 2018; Sahoo and Ghose, 2021).

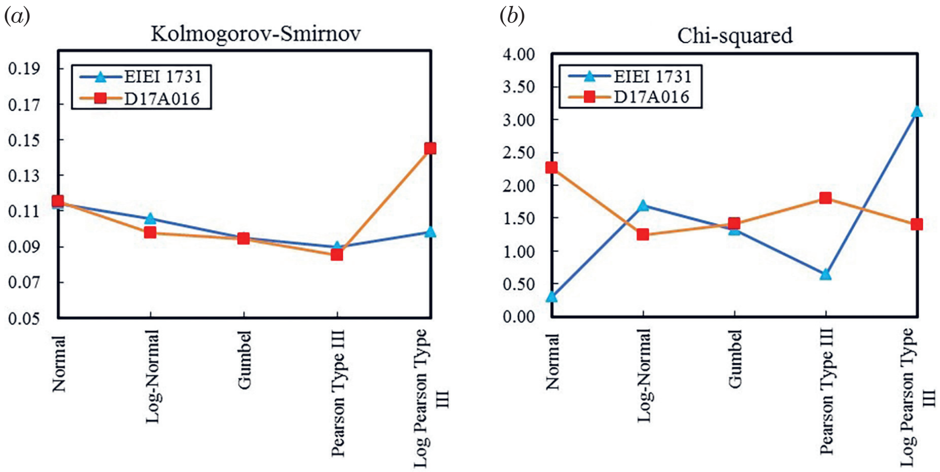

Figure 5. (*a*) Kolmogorov–Smirnov (*b*) Chi-squared goodness-of-fit test results for the stations.

Figure 5 indicates that the compliance values calculated with the Gumbel distribution for both stations were very close to each other according to both the K-S tests and the Chi-square tests. Considering the similar cases in the literature, this result is noteworthy.

It can be said that, among the discharge values for different return periods after the K-S tests, the discharges in 25, 50 and 100 years showed a higher level of compliance. The Normal distribution exhibited the greatest deviation for both stations. Similar results can be seen in the research of Langat et al. (2019) and Samantaray and Sahoo (2020). For both SGSs, the correlation percentage of the Log-Normal distribution was high and the deviations were small.

5. Conclusions

The Eastern Mediterranean Basin, one of Turkey's flood basins, has faced many flood events. Up-to-date basin contingency action plans should be prepared to prevent future floods. Flood frequency analysis is very significant for the preparation of these plans. The estimation of flood discharge plays a key in the planning of hydraulic structures to exploit water resources optimally and to avoid possible disasters. In this study, 36 years of maximum discharge data from two different stream gauging stations (SGSs) numbered D17A016 and EIEI-1731 located in the Eastern Mediterranean Basin, were used to determine flood flow rates for return periods of 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years.

Normal, Log-Normal, Gumbel, Pearson Type III and Log-Pearson Type III statistical distribution functions were employed. While the minimum discharge was obtained with the Normal distribution for both stations, Log-Normal distribution yielded maximum values. The appropriateness of the flood discharge values was investigated by Kolmogorov–Smirnov (K-S) tests and Chi-square goodness-of-fit tests. The K-S tests showed that all probability distributions were compliant at the 20% significance level, and the Pearson Type III distribution was found the most suitable for both stations, considering the goodness-of-fit test ranking. The lowest value for the SGS EIEI-1731 was obtained with the Log-Pearson Type III distribution in the Chi-square test, while Normal distribution produced the lowest value for the SGS D17A016. It is noteworthy that the goodness-of-fit values calculated with the Gumbel distribution for both stations were very close to each other, according to both the K-S tests and the Chi-square tests.

This study contributes to the research on flood and bridge safety. An analysis of water structures, especially historical bridges, in terms of the flood discharge in the region, will pave the way for future researches. Engineering studies will be planned, thanks to these researches, and so loss of life and property in natural disasters such as floods will be prevented to a greater extent.

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SAŽETAK

Modeli razdioba vjerojatnosti za procjenu kritičnog protoka poplavljivanja: Primjer mosta Kravga, Turska

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Posljednjih godina poplave su zbog klimatskih promjena učestale. Kako bi se stanovništvo pripremilo za moguće poplave, važno je na temelju analize učestalosti poplava procijeniti kritični protok poplavljivanja. U ovom radu su analizirani podaci prikupljeni tijekom 36-godišnjeg razdoblja sa dvije hidrološke postaje (SGS, postaje D17A016 i EIEI 1731) smještene u Istočnom Sredozemlju. Vrijednosti kritičnog protoka poplavljivanja izračunate su iz tih podataka za povratne periode od 2, 5, 10, 25, 50, 100, 200, 500 i 1000 godina. Pri tom su korištene normalna, log-normalna, Gumbelova, Pearsonova tipa III i log-Pearsonova razdioba tipa III. Da se odredi koja od razdiobi najbolje opisuje kritični protok poplavljivanja, primijenjeni su Kolmogorov-Smirnovljev (K-S) i χ^2 test. Rezultati su pokazali da je za obje postaje najveći kritični protok poplavljivanja dobiven primjenom log-normalne razdiobe, a najmanji primjenom normalne razdiobe. Rezultati K-S testa pokazali su da je razina signifikantnosti za sve razdiobe vjerojatnosti bila 20%. Interval pouzdanosti određen χ^2 testom za kritični protok poplavljivanja na postaji D17A016 određen log-normalnom razdiobom bio je 90%. Vrijednosti kritičnog protoka poplavljivanja određene drugim razdiobama dobivene dobivene sun a razini signifikantnosti od 10%. Za postaju EIEI 1731 sve razdiobe vjerojatnosti su prema χ^2 testu imale razinu signifikantnosti od 10%.

Ključne riječi: analiza čestina poplava, funkcije razdiobe vjerojatnosti, testovi dobrote prilagodbe, povratni periodi, most Kravga, Turska

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